Improving withstand voltage by roughening the surface of an insulating spacer used in vacuum

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Improving Withstand Voltage by Roughening the Surface of an Insulating Spacer Used in Vacuum

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ABSTRACT

This paper describes a simple and reliable method of improving the surface insulation strength of a spacer used in vacuum. The method is to roughen the spacer surface to an average roughness R_a higher than 1 or 2 μm. The material of the spacer examined is SiO_2, PMMA, PTFE or Al_2O_3 and their shape is a right cylinder with 10 mm in height and 54 mm in diameter. The spacer is subjected to a ramped dc voltage and its surface charging is observed by using an electrostatic probe embedded in the cathode. It has been found that R_a decisively affects the charging, which decreases as R_a increases. Increasing R_a larger than about 2 μm suppresses the charging until a higher applied voltage is reached, thus improving the insulation property.

Index Terms — **Charging, flashover voltage, insulating spacer, roughness, vacuum.**

1 INTRODUCTION

SURFACE discharge along solid insulators (spacers) is an important factor to be considered in designing high voltage vacuum devices. In vacuum, the charging along the surface of an insulating spacer precedes the flashover. The charging takes place through a process in which electrons released from a triple junction, where the cathode, insulator and vacuum meet, propagate toward the anode causing a secondary emission electron avalanche (SEEA) along the insulator surface [1]. Thus, it is believed that the secondary electron emission characteristics have a pronounced effect on the charging and eventually on the withstand voltage.

According to a report by Kawai et al. [2], surface polishing leads to an increase in the secondary emission yield. Bommakanti et al. [3] have pointed out that surface polishing results in withstand voltage reduction. The authors have reported that increasing surface roughness delays considerably the surface charging due to pulsed voltage excitation [4].

This study aims at clarifying quantitatively the relationship between surface roughness and insulation strength in order to obtain useful data for designing an efficient insulating spacer in vacuum. We have examined flashover and charging characteristics of a cylindrical insulator having various degrees of surface roughness under ramped dc voltage excitation. Charging is observed using an electrostatic probe embedded in the cathode. Also, we have conducted the simulation of electron trajectories to discuss the influence of roughness on charging.

Based on these experimental and simulation results, we clarify the influence of surface roughness on insulation strength and charging of insulating spacers in vacuum.

2 EXPERIMENTAL

The insulating spacers studied are made of fused quartz (SiO_2), Polymethyl methacrylate (PMMA), Alumina (Al_2O_3. 92% purity) or Teflon® (PTFE), in the shape of a cylinder with 10 mm height and 54 mm diameter. These specimens were subjected to a ramped dc voltage at a rising rate of 0.25−2 kV/s.

The SiO_2 insulator has an average roughness R_a of 0.03−3.07 μm (5 classes). The specimen with 0.03 μm roughness was polished to a mirror-like smoothness by using buff, and the others were processed by using an emery wheel having various grain sizes.

The PMMA insulator has $R_a = 0.13{-}27.1$ μm (8 classes). The specimens with roughness of $R_a = 0.13$, 0.19

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Table 1. Properties of the insulating materials examined.

	R_a (μm)	δ_{max}	$A_{\delta max}$ (eV)	ϵ_r
SiO_2	0.03−3.07	2.9[5]	400	3.6
PMMA	0.13−27.1	2.3[6]	240	3.0−4.0
PTFE	0.25−37.8	2.1[6]	400	2
Al_2O_3	0.13−11.5	5−7[2]	0.8−2 k	9

and 0.22 μm were polished to mirror-like smoothness using a polymer-polishing compound. The specimens with $R_a = 0.71$, 1.70 and 3.05 μm were roughened by using emery papers having different grain sizes. The other PMMA specimens, $R_a = 6.01$ and 27.1 μm, were mechanically processed by using a lathe, and therefore, they had a spiral scare on the surface.

The PTFE spacer has $R_a = 0.25−37.8$ μm (7 classes). The specimen with $R_a = 0.25$ μm was polished using a polymer-polishing compound. The specimens with $R_a =$ 0.58, 1.30 and 2.0 μm were roughened by using emery papers. The other PTFE specimens, $R_a = 4.66$, 8.06 and 37.8 μm, were processed by using a lathe.

The Al_2O_3 insulator has $R_a = 0.13−11.5$ μm (7 classes). Four of them ($R_a = 0.13−0.37$ μm) were polished with diamond powder, and the other specimens, except for one ($R_a = 1.43$ μm), were processed using a lathe with a diamond bite. The 1.43 μm specimen was made by sintering without mechanical processing (i.e. original surface).

In order to remove various contaminants that would remain on the insulator surface during the roughening or polishing process, each insulator was cleaned by using an ultrasonic vibrator, then rinsed with distilled water and dried before installing in a test vessel. Table 1 summarizes the above-mentioned roughness R_a together with other properties such as the maximum secondary electron yield δ_{max}, its impinging energy $A_{\delta max}$ and the relative permittivity ϵ_r.

The experiment was performed in a test vessel evacuated to 1×10^{-3} Pa by using a turbo molecular pump connected to a rotary pump. The probe is a ring shaped part isolated from the grounded planar cathode and is located coaxially with the cylindrical specimen as shown in Figure 1. We use this probe arrangement to observe the charging process of the insulating spacers without disturbing the geometrical electric field distribution in the gap. Also, as the probe surface is entirely covered by the insulating spacer, this arrangement guarantees the electrostatic charge measurement, where no charge flows into the probe through the vacuum. The probe is grounded through a capacitor, and its signal is converted into electric field strength E_{TJ}, which is the sum of the geometrical field component E_g and the surface charge component E_s. $E_{TJ} = E_g + E_s$. The geometrical field E_g equals to V_{ap}/d, where V_{ap} is the applied voltage, and d the electrode separation. Further details of the probe measurement have been described in a previous paper [7].

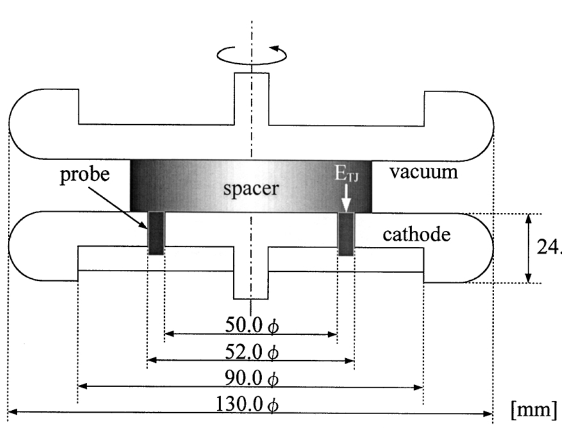


Figure 1. Arrangement of an insulator and a probe.

In order to avoid shot-to-shot variations of the charge measurement due to remnant charge on the insulator surface, it was neutralized each time before conducting the successive measurement. The remnant charge was effectively neutralized by a silent discharge which took place when a small amount of air was introduced into the vacuum vessel. When flashover tests were performed to investigate the withstand ability of an insulator, the above procedure was not adopted until ten flashover voltages were measured. This is mainly to save experimental time. When the neutralization procedure was adopted after each of the successive flashovers, we obtained a flashover voltage a little lower (ca. 10%) than that without the neutralization.

3 FLASHOVER CHARACTERISTICS

3.1 FLASHOVER RECORDS

Each specimen is subjected to 10 ramped voltages to measure the flashover voltage. Figure 2 shows the records of flashover voltage in series of voltage application for SiO_2 and PMMA specimens. It can be seen that the flashover voltage is higher for a larger roughness for both

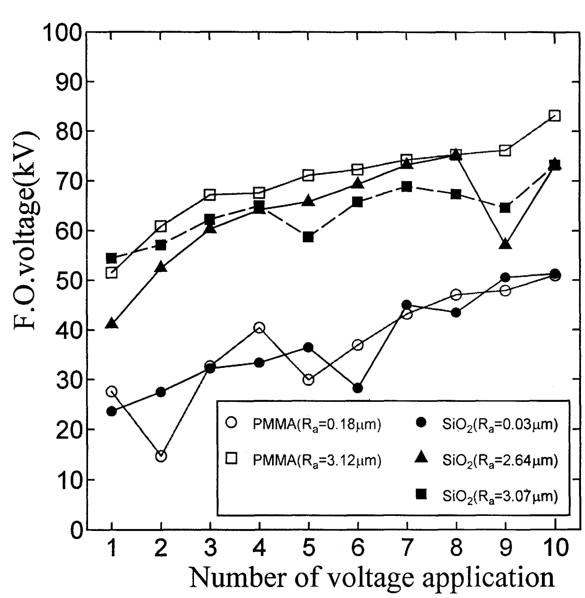


Figure 2. Flashover records of SiO_2 and PMMA insulators.

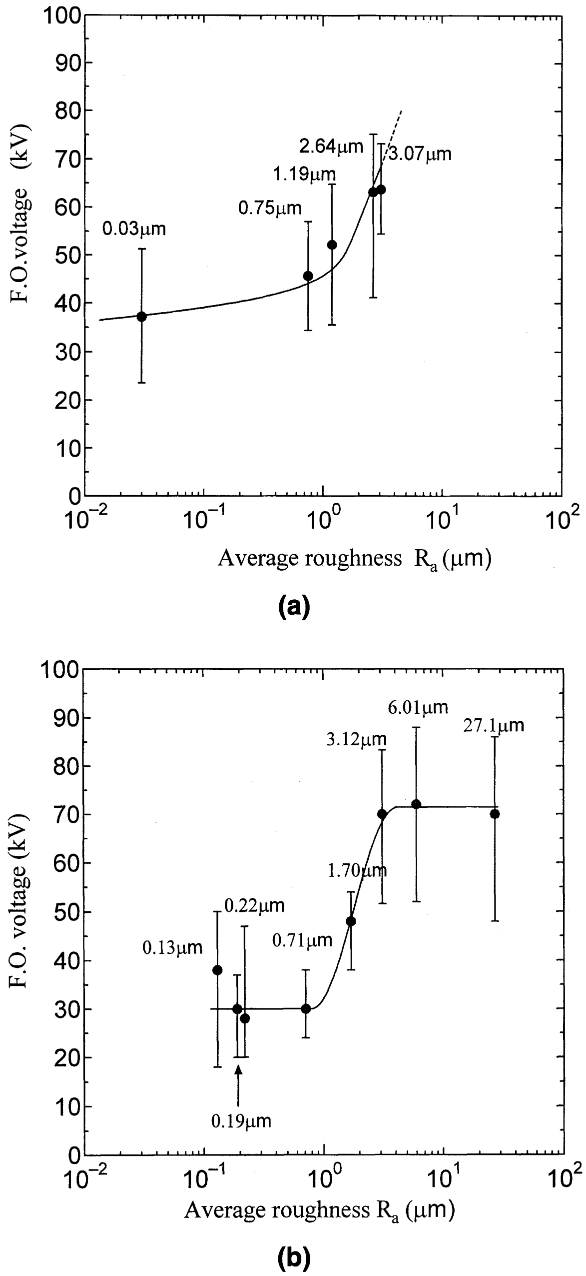


Figure 3. Flashover characteristics of SiO_2 and PMMA. a, SiO_2; b, PMMA.

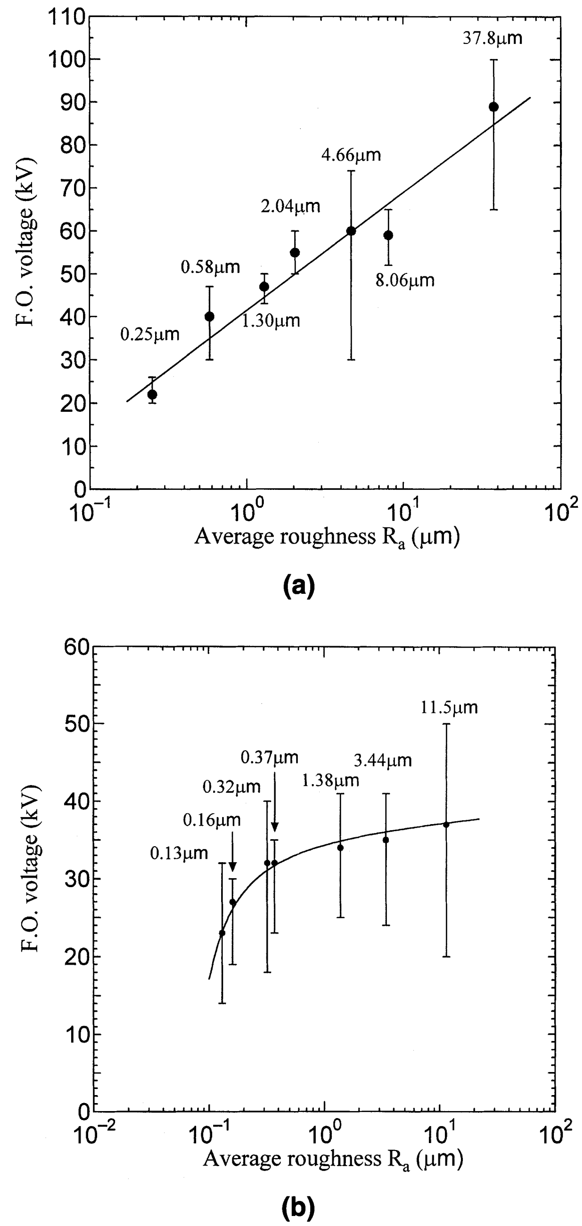


Figure 4. Flashover characteristics of PTFE and Al_2O_3. a, PTFE; b, Al_2O_3.

materials. Note that the first flashover voltage increases also with the roughness. The flashover records for SiO_2 and PMMA are very similar if the surface roughness is close to each other.

3.2 INSULATION STRENGTH

Ten flashover voltages in a consecutive experiment in Figure 2 are averaged for each specimen and shown as a function of the roughness in Figures 3a and 3b, respectively, for SiO_2 and PMMA. The error bars in these figures indicate the minimum, usually the first, and the maximum, the last, flashover voltages of the ten shots. The increase in the average flashover voltage is distinct when the surface roughness is larger than about 1 μm for both materials.

Figures 4a and 4b show the corresponding results for PTFE and Al_2O_3. For PTFE, the average flashover voltage increases almost linearly, on the semi-logarithmic scale, with the roughness ranging from 0.25 to 37.8 μm. The flashover voltage of Al_2O_3 increases with increasing roughness from 0.13 up to 0.32 μm, but it becomes saturated for larger roughness.

One of the important results in the above experiments is that the first flashover voltage for a series of voltage applications increases with the surface roughness. This result is shown in Figure 5 for the four materials. Although

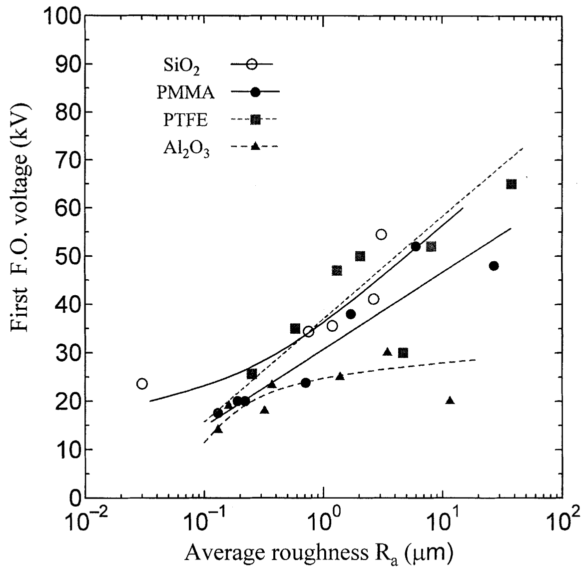


Figure 5. The first flashover voltage as a function of R_a.

the first flashover voltage shows saturation for Al_2O_3, it increases almost linearly on the semi-logarithmic scale with the roughness for SiO_2, PMMA and PTFE. This fact indicates that, by roughening the insulator surface, we obtain higher insulation strength before conditioning with sparks.

4 SURFACE CHARGING

4.1 SiO_2 INSULATOR

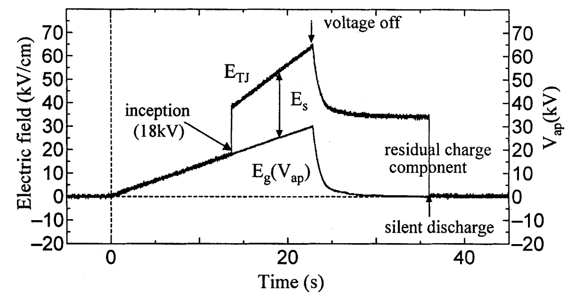
Figure 6a shows an example of simultaneous measurement of an applied voltage V_{ap} and a probe signal E_{TJ} when a SiO_2 insulator with a smooth surface is subjected to a ramped voltage.

The geometrical field E_g, V_{ap}/d ($d = 10$ mm), is plotted on the left ordinate. When the charging starts, the surface charge component E_s is superimposed on the geometrical field. The charging starts suddenly at 18 kV and after inception the charge component increases almost linearly with the applied voltage. The applied voltage was turned off at 30 kV in this case. Even after the voltage is removed, the electric field due to the residual charge on the surface remains. As already mentioned, the residual charge is neutralized by a silent discharge after the voltage removal.

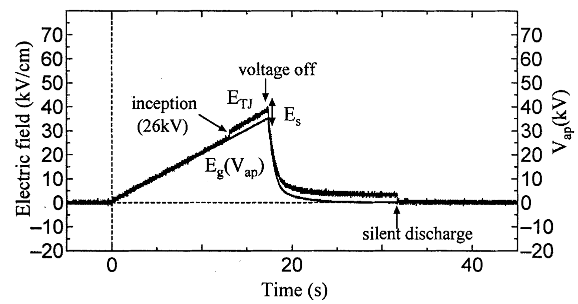
Increasing the roughness raises the inception voltage and decreases the surface charge component as can be seen in Figure 6b. The surface charge component eventually disappears for larger roughness as shown in Figure 6c.

4.2 PMMA AND AL_2O_3 INSULATORS

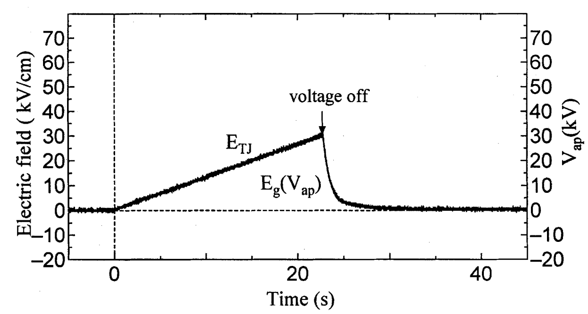
PMMA and Al_2O_3 insulators show similar charging process except that the charging of these insulators starts at a much lower applied voltage. It is 6−7 kV for PMMA and 6−10 kV for Al_2O_3. Furthermore, in the Al_2O_3 insulator case, the surface charge component increases by steps for comparatively rough surfaces. Figures 7a, 7b and 7c demonstrate the change in the probe signal with three classes of surface roughness.



(a) $R_a = 0.03$ μm



(b) $R_a = 1.19$ μm



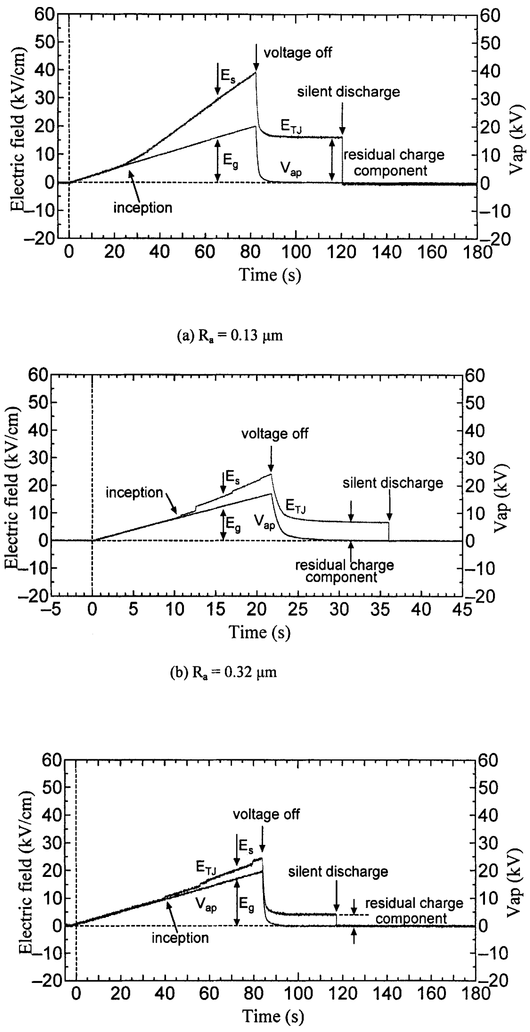
(c) $R_a = 3.07$ μm

Figure 6. Change in probe signal with surface roughness (SiO_2).

4.3 PTFE INSULATOR

PTFE insulators scarcely acquire the surface charge under an applied voltage below 40 kV irrespective of surface roughness. We observed the charging only once for the smoothest specimen. However, even these PTFE insulators acquire surface charge, irrespective of surface roughness, if the applied voltage becomes close to the flashover voltage. The charging in such cases is demonstrated in Figure 8.

A peculiar nature of PTFE insulators has been pointed out by Chalmers et al. [8], that the polarity of charge changes from negative to positive as the applied voltage increases. They attributed this phenomenon to the influ-



(a) $R_a = 0.13$ μm

(b) $R_a = 0.32$ μm

(c) $R_a = 1.38$ μm

Figure 7. Change in probe signal with surface roughness (Al_2O_3).

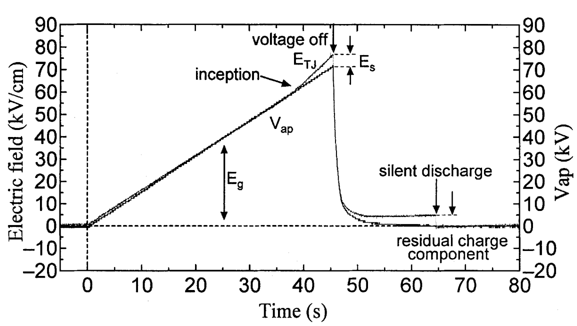


Figure 8. Charging of a PTFE insulator with rough surface.

ence of tribo-electricity. We checked the potential of a PTFE insulator set on a grounded electrode by using a surface potential meter. We have found that the surface potential is negative and decreases to -3 kV. Such potential could be formed by only a touch of a finger covered with a polymer or a paper. In the case of the other materials used in this study, the surface potential was always positive.

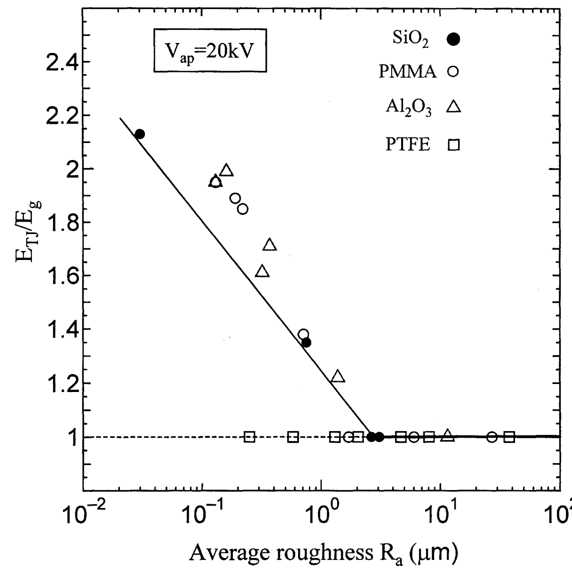


Figure 9. Magnitude of acquired charge at 20 kV.

As the measured surface potential of PTFE is low compared to the applied voltage, we have not taken it into consideration in this study. However, we need a further study on the influence of frictional charge as it might affect the charging onset voltage level that depends on the material.

4.4 DEPENDENCE OF E_{TJ}/E_g ON ROUGHNESS

We summarize the characteristics of charging in terms of the surface roughness. Figure 9 shows the normalized electric field strength (E_{TJ}/E_g), which demonstrates the magnitude of surface charge, as a function of surface roughness when the applied voltage is 20 kV. It can be seen that the surface roughness decisively affects the charging of SiO_2, PMMA and Al_2O_3 insulators.

The surface charge magnitude of these insulators decreases linearly with roughness on a semi-logarithmic scale, and becomes zero for R_a larger than 1 or 2 μm. It needs a higher voltage to cause charging on these insulator surfaces. Furthermore, the difference in the magnitude is small among these three materials.

4.5 FLASHOVER AND CHARGING CHARACTERISTICS

Although the mechanism that can explain the process from surface charging to flashover is not clear at the moment [9], the charging characteristics of SiO_2 and PMMA suggest that the flashover becomes hard to take place when the surface roughness R_a is larger than 1 or 2 μm. This is in good agreement with the results shown in Figures 3a and 3b, where the flashover voltages of SiO_2 and PMMA show, respectively, a distinct increase at nearly the same roughness.

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The spacer made of Al_2O_3 shows almost the same charging characteristic, however, its flashover characteristic is different from those of SiO_2 and PMMA. That is, both the first and the average flashover voltages saturate with increasing roughness. The Al_2O_3 has an extremely high relative permittivity as indicated in Table 1. Thus, it is possible that with imperfect contact between the insulator and the cathode, the electric field strength at the cathode triple junction is so high as to cause discharge relying on a mechanism independent of the charge magnitude. We will conduct a further experimental study on this point by changing the contact condition.

5 DISCUSSION

According to our previous studies, cylindrical insulators subjected to high voltage in vacuum acquire positive charge on the surface that results in enhancement of the electric field at the cathode surface near the triple junction [4,7]. The mechanism of charging has been well established by Boersh et al. [1].

Roughening the insulator surface inevitably modifies the potential of the triple junction. That is, the circumference corners at both ends of a cylindrical insulator are roughened too, which would result in imperfect contact at the cathode junction. Thus, one may consider that roughening the insulator would increase the field emission of electrons and facilitate the charging. However, the experimental result shows the opposite characteristic as in Figure 9.

In order to investigate the influence of surface roughness on charging, we calculated trajectories of secondary electrons and analyzed their hopping height from the insulator surface. The insulator had the same diameter and height as used in the experiment. The injection point of an initial electron was 10 μm away from the junction on the cathode. When releasing an initial electron from the cathode, we assumed that the insulator surface had already been charged at an equilibrium state, in which the charge distribution was such that the secondary electron yield was unity all over the surface [1]. The charge density which depends on the insulator material and the voltage level being applied [10] in turn influences on the hopping height. A Monte Carlo technique [10] was employed for the trajectory simulation.

Figure 10 shows an example of trajectories calculated for PMMA specimen having an ideal smooth surface. The applied voltage is fixed at 20 kV and the secondary electron energy A_s is assumed to be 13 eV. We have chosen a comparatively high A_s to estimate a larger hopping height which would meet the simulation purpose. The average hopping height h_e of the secondary electrons is approximately 0.3 μm. Note that this height is considerably smaller than the insulator roughness when charging no longer occurs ($R_a = 1{-}2$ μm; See Figure 9). Thus, in the case of an insulator with a roughness larger than h_e, the projections on the insulator surface act as barriers for secondary electrons by interrupting their movement. This means that it is hard with the projections to reach the equilibrium state that is expected for a smooth insulator. We believe that this is the main reason why the surface roughness decisively affects charging.

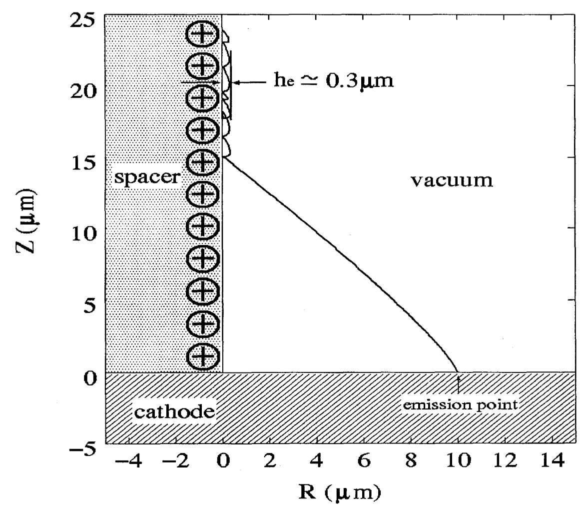

Figure 10. Simulated electron trajectory for PMMA at $V_{ap} = 20$ kV.

6 CONCLUSION

THE surface roughness of an insulating spacer decisively affects both surface charging and flashover voltage for most of the materials examined in this study. Increasing the roughness prevents surface charging and increases the flashover voltage. For SiO_2, PMMA and Al_2O_3, roughness larger than an average of 1 or 2 μm is necessary to prevent charging (at 20 kV; specimen length 10 mm). According to the simulation results, surface protrusions act as barriers against the movement of secondary electrons in the SEEA process.

The first flashover is extremely significant in practical vacuum insulation systems, because the high energy at the flashover is likely to damage the insulator and/or the surrounding metallic parts. Roughening the insulator surface is clearly effective to increase the first flashover voltage for insulator materials such as SiO_2, PMMA and PTFE. We believe that the quantitative data of this study present useful information for designing an insulating spacer for high voltage vacuum devices.

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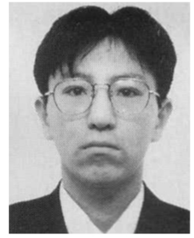

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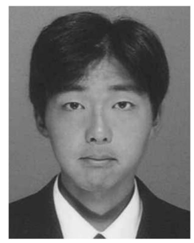

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